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Identification of non-relativistic heavy primaries in cosmic radiation by photometric measurements in nuclear emulsions

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With 5 figures in the text

SUMMARY

The possibility is discussed of determining the charge of a non-relativistic heavy primary particle by photometric measurements of mean track width (MTW) and the rate of change of mean track width along the track. The error in the charge determination is sensitive to the length of the track measured and the particle velocity. Correct identification is possible as soon as the total track length is greater than 25 mm and the momentum of the particle, p_Z, is less than a value which depends on the charge. The limit is for magnesium $p_{12} \simeq 1.2$ GeV/c per nucleon and for iron $p_{26} \simeq 1.5$ GeV/c per nucleon. In an interval 1.2–1.7 GeV/c per nucleon for magnesium and 1.5–2.0 GeV/c per nucleon for iron the rate of change of MTW is too small to be used for identifications. If a particle falling in this interval is identified solely from MTW measurements the apparent charge will be one unit too high. For $p_{12} > 1.7$ GeV/c per nucleon and $p_{26} > 2.0$ GeV/c per nucleon correct identification is possible from the MTW value only.

Introduction

A non-relativistic heavy primary particle in the cosmic radiation is usually identified in nuclear emulsions either by measurements of ionization and small-angle scattering [1] or by its interaction with emulsion nuclei [2]. The scattering-ionization method is suitable for tracks which are undisturbed by the distortion in the emulsion, that is for tracks which are only slightly inclined to the emulsion plane, and especially to flat tracks in glass-backed emulsions. As has been shown in previous papers [3, 4], the most accurate determination of the ionization by photometric measurements is obtained on tracks which pass through and are measured in several pellicles. In this case the influence of occasional irregularities in the emulsions is reduced and a better result of the determination of the ionization is obtained. Thus, the tracks which are most suitable for measurements of ionization, have a fairly large dip angle and are unsuitable for measurements of small-angle scattering.

This paper contains a description of a method of determining the charge of non-relativistic particles by measurements of ionization and the rate of change of ionization along the tracks. The study has been confined to particles with the nuclear charge $Z \geqslant 8$. The restriction to this charge region is due to the need for a method of identifying non-relativistic particles in an investigation of the particle spectrum in the charge region $Z \geqslant 8$ at a geomagnetic latitude of 41° [4]. At this latitude and at balloon altitude a certain number of non-relativistic particles with high charge is to be expected. Such particles will be wrongly identified if they are assumed to be relativistic and if only one parameter, the ionization, is measured.

Emulsion data

Tracks of heavy particles have been measured in a stack of 40 sheets of Ilford G 5 emulsion exposed in Texas, U.S.A., in January 1955, at a geomagnetic latitude of 41°. The floating altitude of the balloon was 29 km, and the time of flight was 8 hours.

The emulsions have been processed according to the temperature development method. The degree of development is normal, the plateau value for singly-charged particles being 19 blobs/100 μ. The background of tracks of slow electrons is fairly high.

Selection criteria

As has been mentioned earlier, only particles with the nuclear charge $Z \geqslant 8$ have been selected. No measurements were made at a distance less than 10 mm from the edge of the emulsion. Only tracks with total projected track lengths > 25 mm in the remaining region of the pellicles are accepted. $\frac{2}{3}$ of the total projected lengths of the tracks have been measured. In each plate about $\frac{1}{6}$ of the track length has been left out near the surface and the same length near the glass. The dip angle, α, must fulfil the condition $\tan \alpha \leqslant 0.45$ in the unprocessed emulsion. A particle to be accepted must furthermore pass through and be measured in at least 6 emulsions. The reasons for these selection criteria are discussed in papers by Waldeskog and Mathiesen [3] and Kristiansson, Mathiesen, and Waldeskog [4].

The photometric measurements

The ionization has been determined by a photoelectric instrument which measures the area of the track. This area depends on the ionization, and from area measurements the ionization of a particle can be obtained. The photometer has been described by von Friesen and Kristiansson [5], and the electronic arrangement for the registration of the measurements by von Friesen and Stigmark [6]. The dimensions of the slit have been changed to suit measurements on tracks of multiply-charged particles. The size is 0.25 mm × 3.0 mm, which is equal to 4.5 μ × 54 μ in the object plane. The objective is a Leitz Ks 53×.

The measuring technique has been slightly modified to be more suitable for measurements on heavy tracks. In the same way as in earlier measurements the area of a section of a track is determined from three readings, one with the slit covering the track and two with an empty slit giving the light background. The difference between the mean value of the two background readings and the first reading determines the area. The background is measured above and below the track with a defocusing of 30 μ in each direction as distinguished from earlier measurements where the background was measured on both sides of the track. The photometric measuring technique of heavy primaries has been studied by Waldeskog and Mathiesen [3].

Several corrections are necessary in photometric measurements on thick tracks. They are discussed in the paper by Waldeskog and Mathiesen [3] and also in the paper by Kristiansson, Mathiesen, and Waldeskog [4]. The discussion will not be repeated here. A very important factor in measurements of rate of change of mean track width is the normalization of MTW values between the plates. Normalizing factors for each plate are determined from tracks of relativistic particles passing through several pellicles in combination with the MTW values of tracks of relativistic oxygen and magnesium nuclei in different parts of the stack [4]. The accuracy in these factors is high, the total error from the first to the last pellicle in the stack being not larger than about 1 %.

Charge determinations by measurements of ionization and rate of change of ionization

Before the discussion proceeds further it seems to be important to investigate whether as a principle a charge determination can be performed by measurements of ionization and rate of change of ionization along the particle path. If the method is capable of use, it must be such that it always gives a single-valued solution to the question of the size of the charge for a given set of values of ionization and rate of change of ionization.

The energy loss of a charged particle passing through matter is determined by Bethe's formula,

$$-\frac{dE}{dR}=J=\text{const}\frac{Z^2}{\beta^2}f(\beta)$$

where $f(\beta)=\ln\frac{2\,m_e\,\beta^2\,c^2}{I}-\ln(1-\beta^2)-\beta^2$, and E, R, J, and β are kinetic energy, residual range, ionization, and velocity of a particle with mass M and charge Z, and I is the mean excitation potential (331 eV).

Differentiation and use of the kinetic energy formula gives the rate of change of ionization along the track:

$$\frac{dJ}{dR}=J^2\frac{1}{M\,c^2}\frac{(1-\beta^2)^{3/2}}{\beta}\left(\frac{2}{\beta}-\frac{f'(\beta)}{f(\beta)}\right).$$

In Fig. 1 relations between J and dJ/dR are shown for some multiply-charged particles passing through nuclear emulsions. As can be seen, curves with consecutive Z values are well separated. Charge determination is accordingly possible by measurements of ionization and rate of change of ionization, if these two parameters can be determined with satisfactory accuracy. It is worth noticing that the ionization must be measured with much higher precision than the rate of change of ionization in order to get satisfactory resolution. This is favourable to the method because as a rule ionization is much easier to measure accurately than the rate of change of ionization.

Photometric measurements on a track according to the Lund method do not determine the ionization directly but the mean width of the track (MTW). This mean width is however a function of the ionization. In the present discussion we have assumed that MTW is a function of the amount of energy loss in the track only, and

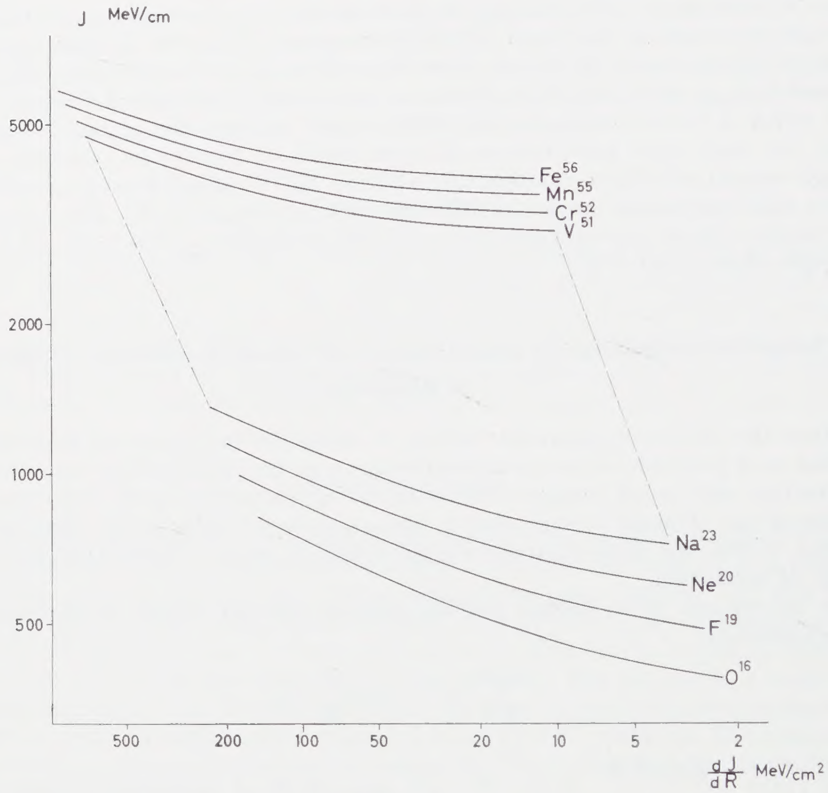

Fig. 1. Relations between energy loss and rate of change of energy loss along the track in tracks of multiply-charged particles in nuclear emulsions.

independent of how it is distributed around the path of the particle. The error from this approximation seems to be small in comparison to other errors in the determination of the rate of change of mean track width.

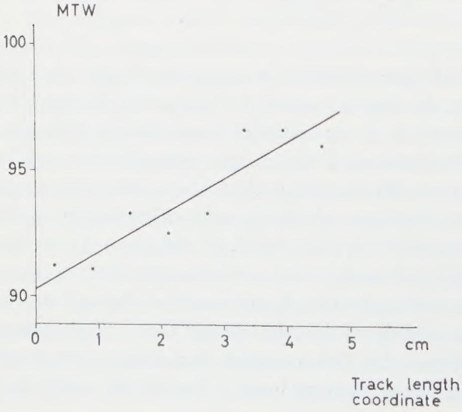

Fig. 2. Mean track width versus the track length coordinate for a non-relativistic chromium nucleus.

Fig. 2 shows an example of a particle where identification by measurements of MTW and the rate of change of MTW is possible. Mean track width is plotted against the track length coordinate for a particle which has been identified as a non-relativistic chromium nucleus.

The MTW value to be used in the identification is the mean value of all measurements along the track. The $\Delta\,\mathrm{MTW}/\Delta R$ is the slope of the straight line approximating the MTW—range relation. A straight line approximation is always satisfactory and does not give rise to systematic errors. The rate of change of mean track width is calculated by the method of least squares.

The rate of change of mean track width

Whether a particle can be identified by the method discussed in this paper depends on the accuracy with which the rate of change of MTW can be determined. In order to study the errors and also to find the non-relativistic particles we have calculated $\Delta\mathrm{MTW}/\Delta R$ for all particles in the stack which fulfil all criteria concerning charge, track length, number of pellicles, and dip angle previously stated. In all, 65 particles fulfil all conditions.

Fig. 3 shows the distribution of the $\Delta\,\mathrm{MTW}/\Delta R$ values. Most of the values are symmetrically distributed around $\Delta\,\mathrm{MTW}/\Delta R = 0$ but a large tail of positive values exists. The symmetrical part of the histogram contains relativistic particles and also some nearly relativistic particles with such small $\Delta\,\mathrm{MTW}/\Delta R$ values that photometric measurements do not give results significantly different from zero. The width of the symmetrical part of the distribution gives information about the accuracy with which $\Delta\,\mathrm{MTW}/\Delta R$ can be measured. Calculations give a standard deviation, $\sigma = 0.25$ units of MTW/cm.

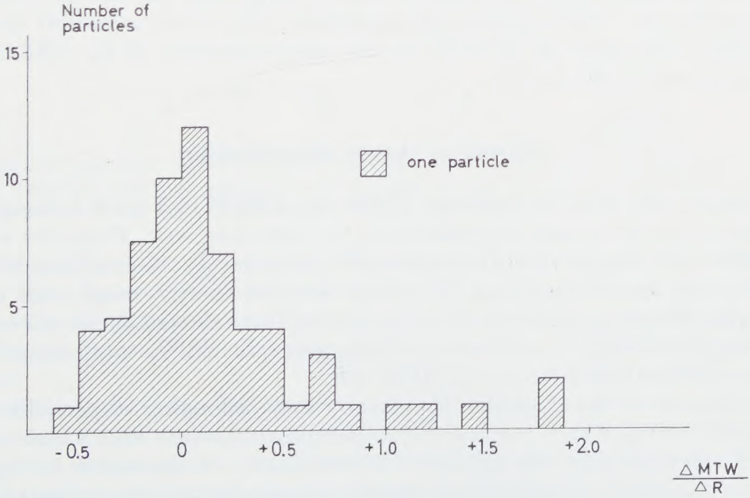

Fig. 3. The distribution of $\Delta\mathrm{MTW}/\Delta R$ for a sample of tracks of particles with $Z \geqslant 8$, found in an emulsion stack flown at a geomagnetic latitude of 41° north. $\Delta\mathrm{MTW}/\Delta R$ is given in units of MTW/cm.

For the correct identification of the largest number of particles it seems to be most favourable to use 2.5 σ as the limit between relativistic particles, which can be identified by MTW measurements only, and non-relativistic particles whose identification requires two parameters, MTW and Δ MTW/ΔR. If the relativistic distribution is assumed to be Gaussian, there will on an average be less than half a relativistic particle outside 2.5 σ in our material. The number of non-relativistic particles falling inside the symmetrical distribution is certainly low but difficult to estimate accurately.

The small number of particles in the histogram has made it impossible to study any variations in the accuracy of particle identification as a fuction of charge or track length. There is a slight increase in the width of the distribution of MTW readings when the charge increases. The consequence must be a slightly larger error in the Δ MTW/ΔR determination. Direct calculations of the error from the MTW distribution is not possible as a very important part of the error comes from irregularities in the emulsions. These irregularities are complicated and not known with sufficient accuracy to be treated with statistical methods.

As has been mentioned earlier, the minimum track length for the particles which have been accepted is 25 mm. The mean value of the track lengths is 36 mm. From our experimental results it has not been possible to draw any conclusions about how the error in Δ MTW/ΔR depends on the track length. In a paper by Johansson and Kristiansson [7] dealing with the identification of singly-charged particles by measurements of MTW and Δ MTW/ΔR, the error was studied as a function of track length. These authors found a dependence

$$\varepsilon(R) = \varepsilon(R_0)\left(\frac{R}{R_0}\right)^{-3/2}$$

in accordance with statistical theory. $\varepsilon(R)$ = the error in Δ MTW/ΔR for a track length = R. As our measuring technique is similar to theirs, we have assumed that our error shows the same dependence on R. $\varepsilon(R_0)$ and R_0 can be obtained from the measurements. With good approximation $\varepsilon(R_0)$ = the standard deviation of Δ MTW/ΔR (0.25 units of MTW/cm in our measurements), if R_0 = the mean value of the track lengths (36 mm).

Method of charge identification

Fig. 4 shows the relations between MTW and Δ MTW/ΔR for the charges $8 \leqslant Z \leqslant 26$. The curves have been determined in the following way. From the relation between MTW and charge valid for relativistic particles [4] the function MTW versus energy loss has been determined. Relations between energy, range, and energy loss for multiply-charged particles have been derived from the emulsion tables of Barkas and Young [8]. Suitable combination of data gives the MTW—range relations, which have been differentiated to give Δ MTW/ΔR.

In the diagram we have plotted 9 measurements belonging to particles with large Δ MTW/ΔR values which we assume to be non-relativistic and which accordingly have to be identified by the method. Unfortunately, in general it is impossible to identify the particles by independent measurements and test the method in this way. But there is at least one striking fact that seems to support the identification. Measurements on relativistic particles in the same charge interval have shown that the number of particles with even charge is much larger than the number of particles

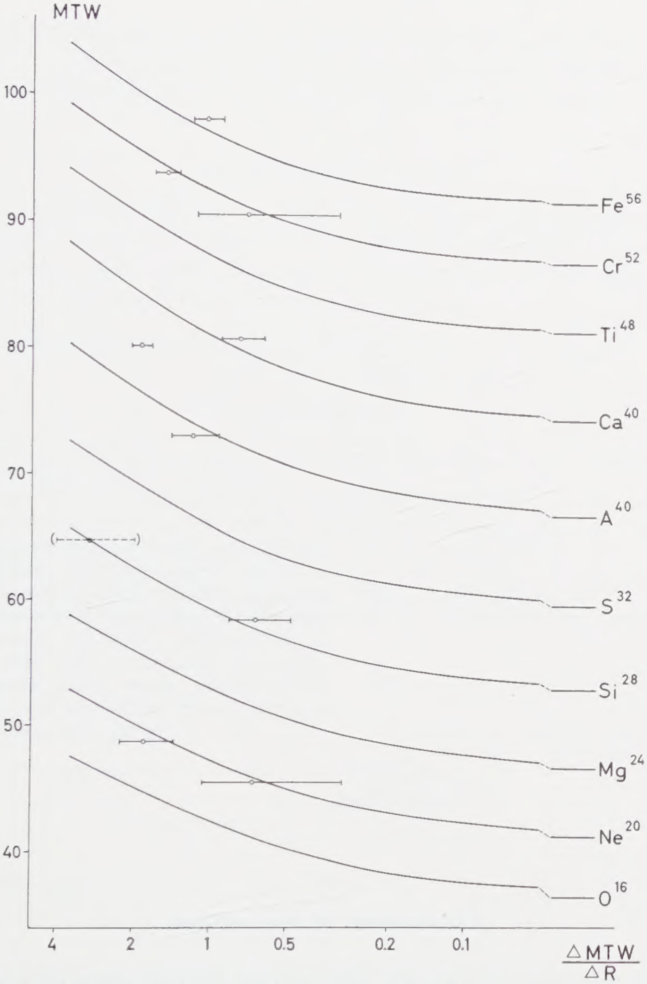

Fig. 4. Computed relations between MTW and ΔMTW/ΔR for non-relativistic particles. The points in the diagram represent measurements on particles which are assumed to be non-relativistic on account of their large ΔMTW/ΔR value. ΔMTW/ΔR is given in units of MTW/cm.

with odd charge. The ratio seems to be of the order of 10. Among the non-relativistic particles we have 8 particles which seem to be even and only 1 odd, thus the same great excess of even charges is found. If the identification was wrong for a large proportion of the particles or the accuracy much lower than expected, this ratio would be about one.

There is one particle in the diagram with MTW = 65 near the Si-curve which has too short a track length to fulfil our criteria for the tracks and to be identified by the method. The comparatively small error shows however that the identification is fairly reliable and together with another interesting feature it justifies its inclusion. The particle interacts with an emulsion nucleus and can be identified from the interaction products as a Si nucleus. The two methods of identification thus agree, which is a further support for the correctness of the identification in the diagram.

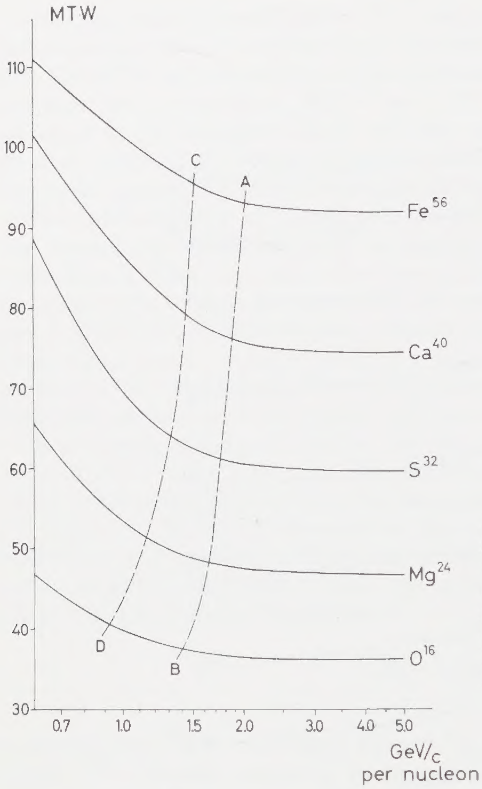

Fig. 5. The figure shows the momentum region in which a heavy particle cannot be identified correctly, neither from measurements of MTW and $\Delta MTW/\Delta R$ nor from measurements of MTW in combination with the assumption that the particle is relativistic. The first method is applicable in the region to the left of the line C–D, and the second method in the region to the right of the line A–B.

Limitations of the method

The previous discussion has shown that correct identification of a non-relativistic multiply-charged particle can be performed from measurements of MTW and $\Delta MTW/\Delta R$ as soon as $\Delta MTW/\Delta R$ is larger than some value depending on the track length and the width of the distribution of the MTW readings. Relativistic particles can be identified by measurements of MTW only. But a region exists where the particles are not relativistic and the $\Delta MTW/\Delta R$ is less than the limit just mentioned, and thus not significantly different from zero. Correct charge identification from pure MTW measurements is not possible in this region. The width of the region is shown in Fig. 5. Particles falling to the right of the dotted line A–B can be correctly identified by measurements of MTW, and particles to the left of the line C–D can be identified by MTW and $\Delta MTW/\Delta R$ measurements. Particles falling in the region between the lines will as a rule be identified from their MTW values giving a charge one unit too high.

The position of the line C–D depends on the track length measured. In Fig. 5 it is drawn for a mean track length of 36 mm. Longer tracks will make the region smaller but the reduction in the width is very slow when the track length increases.

The conclusion to be drawn from the discussion is that most heavy primary particles in the cosmic radiation can be identified correctly by photometric measurements. Only a small fraction of them will be wrongly identified and the error will be one unit of charge.

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